Quantifying the Dynamic Ocean Surface Using Underwater Radiometric Measurements

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LONG-TERM GOALS

The ultimate goal is to develop direct simulation/physics-based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. The simulation-based model will include and integrate all of the relevant dynamical processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transfer (RT).

OBJECTIVES

To develop physics-based modeling and computational prediction and inverse capability for the time-dependent underwater radiative transfer incorporating the dynamical processes on the ocean surface and the upper ocean surface boundary layer (SBL):

- Parameterization of key effects of the dynamical ocean surface on the underwater light patterns and statistics

- Development of new theoretical models and algorithms to substantially speed up forward problem by two or more orders of magnitude

- Establishment of a framework for inverse sensing and reconstruction of ocean surface conditions based on underwater light field measurements

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- Inverse modeling of key flow processes at the sea surface based on underwater light measurement; quantification of the feasibility requirements and limits on applicability of the inverse problem

APPROACH

We developed and applied a highly efficient parallelized Monte Carlo radiative transfer numerical tool to simulate the highly fluctuated underwater light fields (unpolarized and polarized) with very high spatial resolution (up to $O(10^{-3})$mm) (Xu and Yue 2013b). The Monte Carlo RT simulation accounts for effects of the irregular surface waves on the light refractions and reflections for various solar incidence conditions, particularly the shadowing effect for large zenith solar incidence case. With the numerical tool, we investigated the statistical characteristics of the light fields as functions of rough surface boundaries and other ambient environmental conditions. To obtain more realistic dynamic ocean surface conditions, we extended and applied the direct phase-resolved wave simulation based on the efficient high-order spectral (HOS) method and LES capabilities for nonlinear evolution of capillary and gravity waves as well as their interactions with wind and ocean turbulence (Xu *et al* 2011; Xu *et al* 2012). To obtain an efficient approach for statistical inversion of the ocean surface conditions, in addition to previous efforts (Shen *et al* 2011), we developed a new analytical mixture model for probability density function (PDF) of the downwelling irradiance at the upper ocean (Xu and Yue 2013a). The model is fully determined by the variance of the downwelling irradiance and one mixing weight. We provided direct and empirical derivations of parameters needed for the model using priori information of ocean wave spectra, solar incidence and inherent optical properties (IOPs) of ocean. The mixture PDF model presents very accurate predictions with relative errors less than 3% compared with Monte Carlo RT simulation results.

WORK COMPLETED

- **Development of efficient high-resolution Monte Carlo radiative transfer model and direct quantitative comparisons between RaDyO field measurements and model prediction.** We developed the highly efficient Monte Carlo RT model to investigate the statistics of the underwater light fields. The model is capable of predicting high spatial resolution ($O(10^{-3})$mm) fluctuating (downwelling) irradiance. We performed quantitative comparisons and validations, incorporating all key RaDyO waves, IOPs and underwater irradiance measurements with combined wavefield (reconstruction and prediction) and RT modeling.

- **Development of analytical model for probability distribution of the underwater light fields for statistical inversion of the upper ocean surface conditions.** We developed a mixture model for the PDF of the underwater irradiance which is able to accurately quantify the probability distributions of the underwater irradiance for irregular surface wavefields with arbitrary steepness, arbitrary ocean IOPs and broad ranges of detector size. More importantly, the model contains only two physics-based parameters, variance and mixing weight which can be obtained with direct and empirical derivations, respectively, using the factors such as ocean surface slope spectra and IOPs of oceans.

RESULTS

We developed a 3D Monte Carlo (MC) RT simulation capability for highly fluctuated underwater light fields with high spatial resolution. The model was systematically validated by direct comparisons with existing theories and numerical model predictions and with field data including RaDyo measurements. An analytical statistical model for probability distribution of light fields was also developed to understand the underwater light statistics. They provided efficient forward models for further inversion algorithms.

(1) Develop and validate the efficient high-resolution RT model with experiments: We developed a highly efficient parallelized Monte Carlo radiative transfer numerical tool to simulate the highly fluctuated underwater light fields under various irregular ocean surface waves with very high spatial resolution (figure 1a). The light-surface interaction is carefully treated so that shadowing effects and multiple reflections are considered in the RT simulations. Figure 1b shows a comparison between vertical patterns of downwelling irradiance with and without considering the shadowing effect for large solar zenith incidence ($\theta s=85°$). We made extensive cross-calibrations of our simulation predictions with the field data obtained in RaDyO Santa Barbara Channel (SBC) (figure 1c). We applied the measured slope spectrum to the RT simulations and obtained the coefficient of variations (CV) of downwelling irradiance *Ed* and probability distribution of the *Ed*. The figure 1c shows a very good agreement between measured data and our RT simulations.

(2) Develop an accurate mixture model for PDF of underwater irradiance: We developed a new analytical mixture model for probability density function (PDF) of the downwelling irradiance at the upper ocean. We showed that under Gaussian rough sea surfaces, the PDF of Ed can be well described by a Gamma-Lognormal mixture model, which is a linear combination of a Gamma distribution valid in the limit of weak volume scattering and a Lognormal distribution which we derived for the case of strong volume scattering. In figure 2a and 2b, we showed that comparisons of PDF of *Ed* between the mixture model and Monte Carlo RT simulations at three different depths and three different beam scattering coefficients, respectively. It is seen that the mixture model prediction agrees with simulations very well, even for extreme values of the normalized irradiance (up to 10 times of the mean value).

(3) Estimate parameters of mixture model including variance and mixing weight: Since the variance and the mixing weight are the only two parameters of Gamma-Lognormal mixture model, we provided closed-form derivation for the variance of Ed and empirical estimation of the mixing weight (figure 3). In figure 3a, it is shown that the standard deviations of Ed obtained by the closed-form derivation for three different scattering cases agree with those obtained by Monte Carlo RT simulations. In figure 3b, we showed an example of using limited data obtained by Monte Carlo RT simulation for different ocean surfaces (different MSS) to fit the empirical formula, $\mu=1+Ag_0bZ+B(g_0bZ)^2$, where μ is mixing weight, g_0 is the anisotropic coefficient, b is the beam scattering coefficient and Z is the depth; A and B are constant coefficients to be determined by the limited data. It is noted that $0\leq\mu\leq1$. It is seen that that the formula gives a good prediction of the mixing weight for arbitrary ocean surface roughness/steepness.

IMPACT/APPLICATIONS

The capability of accurate prediction of the underwater irradiance probability distribution and variability at the near surface may enable the development of novel statistical approaches for accurate reconstructions of complex ocean boundary layer processes.

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PUBLICATIONS

1. Xu, Z. and D. K. P. Yue (2013a), Mixture model for probability of inherent shortwave radiation intensity in strong scattering mediums with penetrable rough surfaces, *Optics Letter* [submitted]

2. Xu, Z. and D. K. P. Yue (2013b), Monte Carlo radiative transfer simulation for the near ocean surface high-resolution downwelling irradiance statistics, *Optical Engineering* [submitted]
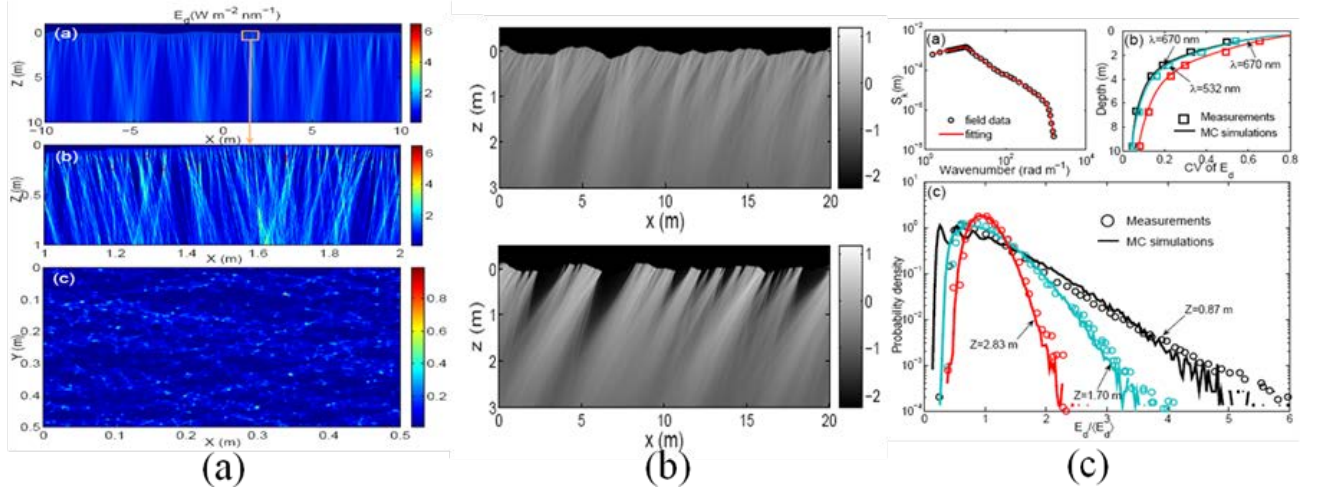
Figure 1. High-spatial-resolution patterns of the underwater downwelling irradiance Ed affected by the ocean surface waves. (a) vertical (upper figure) and horizontal (lower figure)patterns of Ed for small solar zenith angle incidence θs=0˚; (b) vertical patterns of Ed for large solar zenith incidence θs=85˚ without (upper figure) and with (lower figure) shadowing effects; (c) validation of RT model with RaDyO Santa Barbara channel experiments.
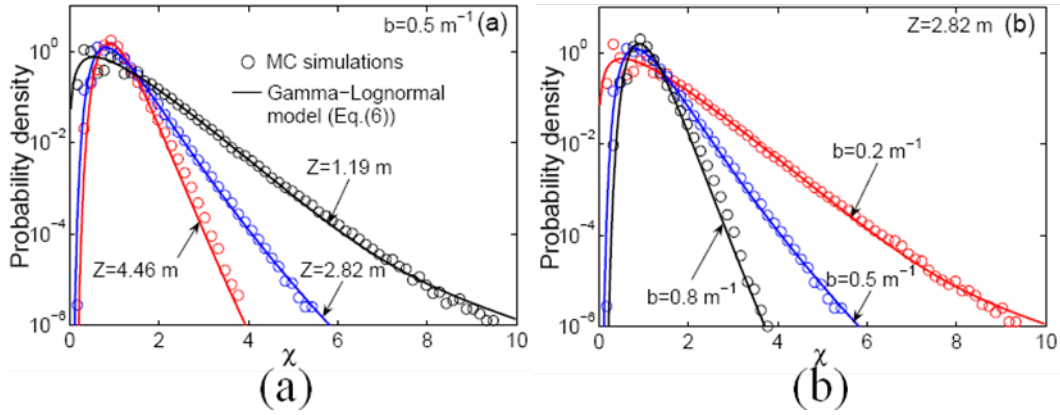

Figure 2. Performance of the Gamma-Lognormal mixture model for the PDF of the normalized average intensity compared to Monte Carlo RT simulation predictions, under a ECKV wave surface of MSS=0.77 and water attenuation coefficient c=1m^{-1}. (a) Scattering coefficient b=0.5m^{-1} for different depths Z=1.19, 2.82, 4.46m, the corresponding model parameter values are σ=0.4564, 0.1479, 0.0806; and μ=0.923, 0, 0. (b) Depth Z=2.82m for different scattering coefficients b=0.2, 0.5, 0.8 m^{-1}, the corresponding model parameter values are σ=0.4762, 0.1479, 0.0728; and μ=0.950, 0, 0.
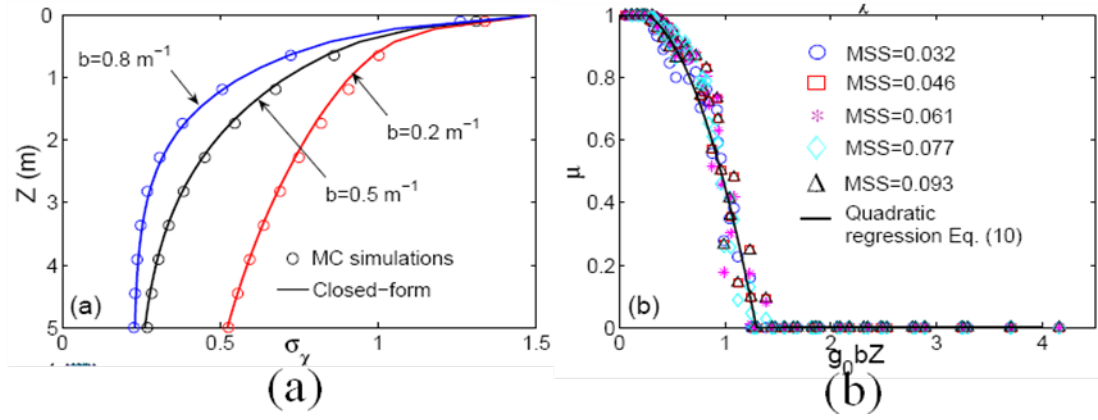
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Figure 3. Estimation of the parameter σ² and μ in the Gamma-Lognormal mixture model. (a) σ² : comparison between results from the closed form expression and Monte Carlo RT simulations. (b) μ: quadratic regression using Monte Carlo RT simulation data. The best fit is given by A=0.20, B=0.75, with R²=0.925.